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## *QUERCUS* POLLEN SEASON DYNAMICS IN THE IBERIAN PENINSULA: RESPONSE TO METEOROLOGICAL PARAMETERS AND POSSIBLE CONSEQUENCES OF CLIMATE CHANGE

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**Abstract:** The main characteristics of the *Quercus* pollination season were studied in 14
different localities of the Iberian Peninsula from 1992-2004. Results show that *Quercus*
flowering season has tended to start earlier in recent years, probably due to the
increased temperatures in the pre-flowering period, detected at study sites over the
second half of the 20th century. A Growing Degree Days forecasting model was used,
together with future meteorological data forecast using the Regional Climate Model
developed by the Hadley Meteorological Centre, in order to determine the expected
advance in the start of *Quercus* pollination in future years. At each study site, airborne
pollen curves presented a similar pattern in all study years, with different peaks over the
season attributable in many cases to the presence of several species. High pollen
concentrations were recorded, particularly at Mediterranean sites. This study also
proposes forecasting models to predict both daily pollen values and annual pollen
emission. All models were externally validated using data for 2001 and 2004, with
acceptable results. Finally, the impact of the highly-likely climate change on Iberian
*Quercus* pollen concentration values was studied by applying RCM meteorological data
for different future years, 2025, 2050, 2075 and 2099. Results indicate that under a
doubled $CO_2$ scenario at the end of the 21st century *Quercus* pollination season could
start on average one month earlier and airborne pollen concentrations will increase by
50% with respect to current levels, with higher values in Mediterranean inland areas.

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Days, Climate Change, predictive models.

## INTRODUCTION

In spring, tree pollen grains of the Fagales order which
includes *Quercus* genus, are a main allergen source in the

northern hemisphere, with cross-reactivity occurring
between pollen within the same order [40, 44]. Several
studies consider *Quercus* pollen type responsible for
allergy in areas with abundant *Quercus* vegetation [5, 38,

46, 52, 56, 57]. The *Quercus* genus is represented in the Iberian Peninsula by 11 tree species commonly known as oaks (cork-oaks, holm-oaks, gall-oaks, etc.). These species are distributed throughout the entire peninsula, are well represented in Atlantic forests and dominate most Mediterranean ecosystems. All are anemophilous trees producing stenopalynus pollen grains (not distinguishable under light microscopy) in high quantities that are well dispersed through the air [29, 58]. The high abundance of these species in natural and semi-natural vegetation areas increases allergy risk for agriculture and forestry-related workers in the Iberian Peninsula, highly exposed to *Quercus* pollen grains [56]. *Quercus* pollen season dynamics and their relationship with meteorological factors were studied at 14 sites of the Iberian Peninsula (Spain). Particular attention was paid to the effect of the detected temperature increase in later years on the *Quercus* pollen season, and to the potential consequences of the global climate change.

In recent years, the rise in winter and spring temperatures as a consequence of global climate change is causing earlier leafing and flowering in many species, in both Europe and the USA [4, 17, 41]. Changes in the pollination period features, both timing and intensity, of plants producing allergenic pollen would have important consequences on allergy sufferers [3, 16]. Knowledge and forecasting of the pollination dynamics provides useful information for managing and preventing allergic symptoms. The effect of recent climate warming on vegetation phenology and aerobiology is an important issue which is being taken into account in climate-change studies [28, 53]. Because *Quercus* pollen emission is a springtime phenomenon, pollen season dynamics are sensitive to changes in phenology.

Global average surface temperature has increased 0.6°C since the late 19th century. Spring temperatures in the Mediterranean countries have risen by 2°C over the last two decades [36, 42]. The increase has been shown to prompt earlier leaf bud bursting and flowering in temperate Mediterranean tree species such as oak and olive [24, 27]. The Special Report on Emissions Scenarios (SRES) produced a series of scenarios of $CO_2$ emissions representing outcomes of distinct narratives of economic development [45]. Scenarios are plausible future states of the climate system. They are derived from predictions of climate change from Global Climate Models (GCMs) based on $CO_2$ emissions scenarios. GCMs are mathematical descriptions of the physical elements and processes in the atmosphere, oceans and land surface (winds and ocean currents, clouds, rainfall, soils). However, in areas where bio-geography has a significant effect on weather, scenarios based on global models will fail to capture local details for impact assessment. The best method for adding these details to global models is to use a Regional Climate Model (RCM), essentially a higher-resolution version of a GCM covering a limited area [48]. Simulation RCM can be replicated by using forecasting phenological models, and allows assessment of the potential variation in

vegetation dynamics [47]. Here, we examine the potential changes on *Quercus* floral phenology in Spain, indicated by airborne pollen dynamics. We use the findings of recent studies and the models developed in this study to drive them with replicated RCM simulations, in order to explore potential changes in *Quercus* pollen season that could accompany future temperature changes in the Iberian Peninsula.

## MATERIAL AND METHODS

**Description of study areas.** The 14 study sites present different climatic, topographic and vegetation characteristics; some of these are summarised in Table 1. Northwest (NW) Spain is a mild-temperature, rainy area influenced by the Atlantic Ocean. The predominant form of vegetation is deciduous woodland, with a large population of *Quercus* species. Vigo and Santiago are located in the Euro-Siberian region, with similar weather and vegetation conditions and low altitude. *Quercus robur* L. (first in flowering) and *Quercus pyrenaica* Willd. are the most common *Quercus* species in the forests of this area. The remaining study areas are situated in the Mediterranean Region, although Ourense and Leon are highly influenced by the Euro-Siberian region climate. The sampling sites located in the northeast (NE) of the Iberian Peninsula, Barcelona, Tarragona, Lleida and Girona, have a typically Mediterranean landscape, with extensive areas of holm oaks (*Quercus ilex* subsp. *ilex* L., *Quercus ilex* subsp. *ballota* (Desf.) Samp), *Quercus humilis* Miller, and *Quercus suber* L.; Kermes oak (*Quercus coccifera* L.) woodland appears on the most impoverished soils. The climate of the first 2 sites is characterised by the proximity of the Mediterranean sea. Temperatures are warm and annual rainfall is scarce. The phenological flowering order is as follows: *Q. humilis*, *Q. coccifera*, *Q. suber* and *Q. ilex* subsp. *ilex* and *Q. ilex* subsp. *ballota* The Central area has a dry, continental climate with significant inter-seasonal variations in both temperature and rainfall. In the local countryside around Madrid, the dominant *Quercus* species is the holm-oak *Q. ilex* subsp *ballota*, which forms large areas of oak-grass savannahs used for livestock farming and known as *dehesas*. Leon, located to the north, is influenced by the Euro-Siberian region. Its landscape is characterised by mid-altitude holm oak woodland, although higher woodland populated by *Q. pyrenaica* and *Q. faginea* Lam. can also be found. These 2 species flower 1 month later than the holm-oak. The Southern region includes 5 of the study sites: Cordoba, Priego, Jaen, Granada and Malaga This region has a warmer, drier Mediterranean climate, with more moderate conditions in the coastal city of Malaga. Typical vegetation includes *dehesas* of holm-oak (first flowering), cork-oaks (last flowering) in the most humid areas with acid soils, and kermes-oak (second flowering) in impoverished soil areas. A few populations of *Q. pyrenaica* and *Q. faginea* grow in deep ravines and humid locations in the Supramediterranean vegetation area.

**Table 1.** Site characteristics: geographical setting in the Peninsula, elevation (metres above sea level), coordinates, mean air temperature, average annual rainfall in millimetres, years of analysed data and *Quercus* species present at each site.

| Zone | Site | Elevation (m) | Coordinates | Mean air temp. (°C) | Mean annual rainfall (mm) | Years of data (studied period) | *Quercus* species |
|---|---|---|---|---|---|---|---|
| North-West | Santiago | 270 | 42°53'N, 8°32'W | 12.9 | 1288 | 9 years (1993-2001) | *Q. robur* (L.) *Q. pyrenaica* (Willd.) |
| North-West | Vigo | 50 | 42°14'N, 8°43'W | 15 | 1338 | 7 years (1995-2001) | *Q. robur* (L.) *Q. pyrenaica* (Willd.) *Q. suber* (L.) |
| North-West | Ourense | 130 | 42°21'N, 7°51'W | 13.8 | 802 | 9 years (1993-2001) | *Q. robur* (L.) *Q. pyrenaica* (Willd.) *Q. suber* (L.) *Q. ilex* subsp. *ballota* (Desf.) Samp. |
| North-East | Barcelona | 90 | 41°24'N, 2°9'E | 16.5 | 595 | 8 years (1994-2001) | *Q. ilex* subsp. *ilex* (L.) *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. humilis* (Miller) *Q. coccifera* (L.) *Q. suber* (L.) *Q. cerrioides* (Willk. & Costa) |
| North-East | Tarragona | 48 | 41°7'N, 1°15'E | 15.8 | 478 | 6 years (1996-2001) | *Q. ilex* subsp. *ilex* (L.) *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. humilis* (Miller) *Q. pyrenaica* (Willd.) *Q. faginea* (Lamk) *Q. coccifera* (L.) |
| North-East | Girona | 125 | 41°54'N, 2°46'E | 15.0 | 740 | 6 years (1996-2001) | *Q. ilex* subsp. *ilex* (L.) *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. humilis* (Miller) *Q. suber* (L.) *Q. coccifera* (L.) |
| North-East | Lleida | 202 | 41°37'N, 0°38'E | 15.1 | 385 | 6 years (1996-2001) | *Q. coccifera* (L.) *Q. ilex* subsp. *ballota* (Desf.) Samp. |
| Centre | Leon | 830 | 42°34'N, 5°35'W | 10.0 | 550 | 8 years (1994-2001) | *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. pyrenaica* (Willd) *Q. faginea* (Lamk) |
| Centre | Madrid | 600 | 40°27'N, 3°45'W | 14.0 | 440 | 9 years (1993-2001) | *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. pyrenaica* (Willd) *Q. coccifera* (L.) *Q. faginea* (Lamk) |
| South | Cordoba | 123 | 37°50'N, 4°45'W | 18.0 | 600 | 10 years (1992-2001) | *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. coccifera* (L.) *Q. suber* (L.) |
| South | Priego | 650 | 37°26', 4°11'W | 14.4 | 650 | 8 years (1994-2001) | *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. coccifera* (L.) |
| South | Jaen | 550 | 36°46'N, 3°47'W | 17.0 | 582 | 6 years (1996-2001) | *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. coccifera* (L.) *Q. faginea* (Lamk) |
| South | Granada | 685 | 37°11'N, 3°35'W | 15.1 | 400 | 10 years (1992-2001) | *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. coccifera* (L.) *Q. suber* (L.) |
| South | Malaga | 5 | 36°47'N, 4°19'W | 18.0 | 575 | 10 years (1992-2001) | *Q. ilex* subsp. *ballota* (Desf.) Samp. *Q. coccifera* (L.) *Q. suber* (L.) |

**Airborne data.** The aerobiological behaviour of *Quercus* pollen was statistically analysed using a 13-year database (1992-2004) of pollen and meteorological data from 14 sites in the Iberian Peninsula (Tab. 1, Fig. 1). These data were drawn from the Spanish Aerobiology Network (REA) data bank held at the REA Coordinating Centre (University of Cordoba). In all the stations, Hirst volumetric spore traps were used. They are located on buildings approximately 15 m above ground level. These traps have an autonomy of 7 days and collect pollen continuously with a given absorption flux, enabling daily and even hourly pollen concentration data to be obtained. Daily mean data are expressed in terms of pollen concentrations per cubic metre of air (gr/m³). The aerobiological methodology recommended by the REA was used [15]. Pattern curves were constructed with 5-day

**Figure 1.** Predicted temperature increase for 2099 in the Iberian Peninsula (Regional Climate Model HadCM3A2a model). The study localities are indicated on the map.

moving-average values calculated from daily values. Graphs were plotted following the line-up method [32]. The Pollen Index (PI) was defined as the total pollen detected in the Main Pollen Season (MPS) of a given year. The start of the MPS was defined as the day on which 1 pollen grain/m³ was reached wherever 5 subsequent days contained 1 or more pollen grains/m³. The end was determined as the last day on which 1 pollen grain/m³ was recorded wherever subsequent 5 days presented concentrations below this level [25]. Data from 1992-2000 were used to build prediction models. These were validated in 2001 and 2004, except in Leon and Priego. In Leon, models were validated in 2000 (not included in the model for Leon) and 2004, due to technical problems that interrupted sampling during the spring of 2001. In Priego, models were validated in 2001 (not included in the model for Priego) and 2002.

**Meteorological data.** The Spanish National Institute of Meteorology (www.inm.es) supplied daily meteorological data from its stations located nearest to the pollen traps. The Iberian Peninsula suffered a severe drought between 1990-1995, mainly affecting Mediterranean areas; as a result, the data were divided in 2 groups for the statistical analysis (except for the NW sites, unaffected by the drought). The extremely dry period, 1992-1995, and the usual climate period, 1996-2000.

**Statistical analyses.** The STATISTICA© software package was used in all analyses. For forecasting daily and annual pollen concentrations, a Spearman correlation test was performed previously to detect the chief variables affecting pollen values. Stepwise multiple regression

analysis was performed in order to construct both daily and annual pollen forecasting models. Predictive variables were chosen by applying a Factor Analysis for Principal Components in order to avoid multi-colinearity. For daily forecasts, previous attempts by analysing the whole season revealed very weak and contradictory results, therefore 2 types of regression models were developed: Pre-Peak models (from the start date up to the maximum-value date); and After-Peak models (from the maximum-value date up to the end of the pollen season). Daily models were developed by constructing general equations comprising several years. For Mediterranean sites, 2 different groups of years were taken into account, to reflect the drought period (1992-1995; 1996-2000). Daily variables, such as weather data from the previous day and accumulated weather data from the previous 2-5 days, and previous and cumulative pollen counts up to the date for which the forecast was made were used as predictive variables. For PI forecasting models, the following were calculated: fortnightly minimum, maximum and mean temperature; fortnightly total rainfall; fortnightly evapo-transpiration and chilling hours based on daily data, to be used as independent variables in order to obtain predictive models for forecasting total annual pollen emission. Future start dates were calculated by applying future meteorological data to a previously-developed thermal forecasting Growing Degree Day (GDD°) method [27].

All predictive models were validated in years not included in the equations. For the daily model, 2 different equations were developed for Pre-Peak and After-Peak pollen curves. Since weather conditions from 2000-2004 were similar to those of 1996-2000 in the Mediterranean area, the proposed forecast formula for that period was used for validation purposes at years 2001 and 2004. Expected vs. actual data were compared graphically. The R2 coefficient and the Wilcoxon matched pairs test were performed between expected and actual data. Annual pollen results were validated by calculating Root Mean Square Error and % Error.

**Simulation model.** Future meteorological data modelled by the Hadley Meteorological Centre including in the Intergovernmental Panel on Climate Change (IPCC), were used for estimating future pollination start dates. The data were obtained through a contract (Contract EPG 1/1/124) signed by Cordoba University and the Climate Impacts LINK Project (Hadley Centre). The present study also analyses the possible future consequences of this expected climate change on the annual amounts of released *Quercus* pollen, based on the forecast equations developed here. The model is a mathematical description of major elements and processes in the atmosphere, oceans and land surface comprising the climate system. By applying statistical downscaling the method adds fine-scale information. This technique uses observation in historical meteorological data sets and today's climate dynamic to derive relationships between large-scale climate variables and the surface climate at point
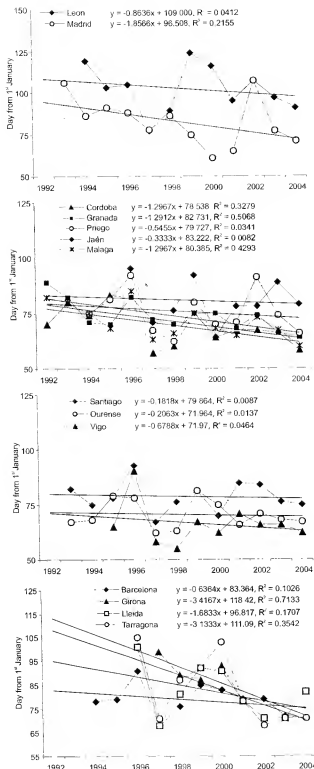
**Figure 2.** Start date variation during 1992-2004 at the 14 study localities (day of the year). Linear trend equation is also represented. The equation values and $R^2$ coefficient for each locality are also indicated.

locations [47]. The climate scenario applied for the end of the 21st century was the x2 $CO_2$ proposed by the IPCC, which assumes a 1% per year increase in $CO_2$ concentrations, which is the most probable expected increase for
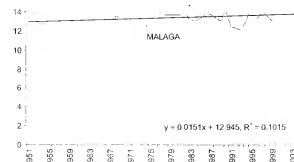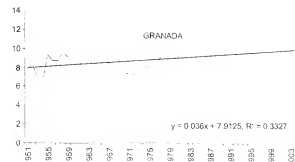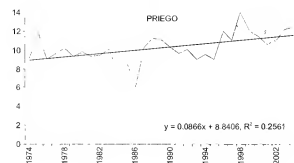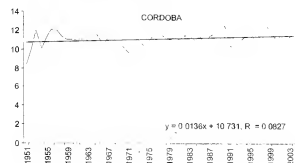
the next years. In this scenario, the HadCM3A2a Regional Circulation Model (RCM) developed by the Hadley Meteorological Centre provided us with future climate data. The RCM provided a horizontal resolution of 50 × 50 km grid cells, which allowed us to obtain a different climatic data base at all study sites (Fig. 1).

**RESULTS**

**Pollen season start and Climate Change.** The pollen season start date variation from 1992-2004 is shown in Figure 2. In this figure, the trend over the years is also plotted for each site. At all sites, the regression trend equation presented a negative slope coefficient, indicating that the start of the flowering season tended to be earlier in later years. This characteristic was more evident in inland central sites such as Madrid and Jaen. Due to the considerable year-on-year variation in start dates, equations are less well adjusted to a linear model, $R^2$ coefficients not being as close to 1. There was an evident gradual advance of the pollen season, which was more obvious in inland than in coastal areas, due to a greater warming in these study areas. Analysis of climate databases (National Institute of Meteorology) shows that temperatures recorded in the Iberian Peninsula have increased considerably. Figure 3 shows average temperature registered in the pre-fl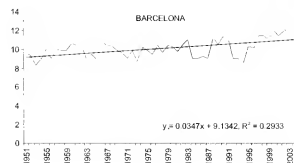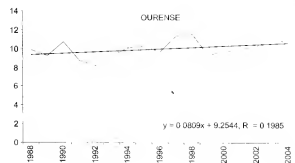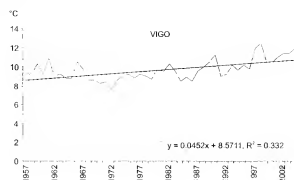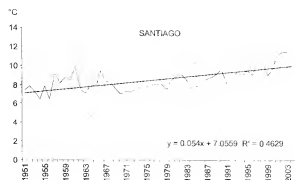owering season (January-March), from 1951 to the present, at all study sites. The positive slope of the trend equations confirmed the increase in temperature.

Using the GDD° model [26, 27], it is possible to assess starting dates for years where climate data, but no pollen observations, are available. To ascertain the potential impact of future climate change on Mediterranean forest, future climate data, HadCM3A2a RCM, were applied to the GDD° model for the years 2025, 2050, 2075 and 2099. The predicted increase in temperature in the Iberian Peninsula varies among sites (Fig. 1). These differences are likely to give rise to marked geographical variations in the advance of phenology (Tab. 2). The predicted minimum advance will be in northwestern sites, such as Santiago, whereas in inland cities like León and Madrid flowering could take place up to 1 month earlier. In Table 2 it is possible to compare the detected advance from the beginning of the 90's until today, with the expected advance for the end of the present century.

**Daily pollen concentrations.** The curves showing daily pollen counts at the various study sites are shown in Figure 4. Generally speaking, the *Quercus* pollen season in the Iberian Peninsula lasted 3-4 months, depending on the vegetation and climate characteristics of the years and areas studied. Several peaks were observed in some cases, mostly due to the consecutive flowering of different species (see section: Description of Sites). Nevertheless, external factors such as spring rainfall or changes in wind direction or speed may also have contributed to a more irregular curve.

°C

**SANTIAGO**

y = 0.054x + 7.0559  R² = 0.4629

°C

**VIGO**

y = 0.0452x + 8.5711, R² = 0.332

**OURENSE**

y = 0.0809x + 9.2544, R = 0.1985

**BARCELONA**

y = 0.0347x + 9.1342, R² = 0.2933

**LEON**

y = 0.0438x + 3.9448, R = 0.3545

**MADRID**

y = 0.0355x + 6.8941, R² = 0.2544

**CORDOBA**

y = 0.0136x + 10.731, R = 0.0827

**PRIEGO**

y = 0.0866x + 8.8406, R² = 0.2561

**GRANADA**

y = 0.036x + 7.9125, R² = 0.3327

**MALAGA**

y = 0.0151x + 12.945, R² = 0.1015

**Table 2.** Actual and expected start dates (day of the year). Advances between different periods are indicated in two last columns.

| Site | Beginning 90's start date (d.y.) | Beginning 21st start date (d.y.) | Beginning 21st beginning 90's (days of difference) | 2025 forecast start date (d.y.) | 2050 forecast start date (d.y.) | 2075 forecast start date (d.y.) | 2099 forecast start date (d.y.) | 2099 beginning 21st (days of difference) |
|---|---|---|---|---|---|---|---|---|
| Santiago | 82 | 80 | -2 | 80 | 79 | 77 | 77 | -3 |
| Vigo | 74 | 65 | -9 | 55 | 50 | 36 | 32 | -33 |
| Ourense | 73 | 69 | -4 | 54 | 48 | 33 | 29 | -40 |
| Barcelona | 90 | 80 | -10 | 77 | 76 | 74 | 75 | -5 |
| Girona | | 85 | | 80 | 75 | 70 | 72 | -13 |
| Lleida | | 84 | | 80 | 77 | 75 | 71 | -13 |
| Tarragona | | 90 | | 80 | 76 | 76 | 75 | -15 |
| León | 115 | 105 | -10 | 90 | 64 | 47 | 31 | -74 |
| Madrid | 106 | 82 | -24 | 65 | 47 | 27 | 26 | -56 |
| Córdoba | 90 | 80 | -10 | 71 | 58 | 31 | 23 | -57 |
| Priego | 91 | 75 | -16 | 59 | 50 | 25 | 25 | -50 |
| Jaen | | 71 | | 50 | 49 | 27 | 28 | -43 |
| Granada | 82 | 75 | -7 | 64 | 54 | 31 | 30 | -45 |
| Málaga | 81 | 73 | -8 | 68 | 54 | 43 | 34 | -39 |
| Mean | 88 | 79 | -9 | | | | 45 | -34 |

Similarities were detected between curves for sites located in the same climate region, probably due to a similar species spectrum and similar meteorological conditions. It was therefore possible to distinguish 4 general patterns in the NW, NE, Central, and Southern areas. Sites located in NW Spain (Figs 4a-4d), displayed low pollen concentrations with 1 peak right at the start of the season and another at mid-season. In the NE area, a lower peak is detected at the beginning of the season and another higher peak at the end (Figs 4e-4h). Very different pollen curves were recorded in the Central sites of Madrid (Fig. 4i) and León (Fig. 4d), Madrid values being substantially higher. Nevertheless, a similar pattern with 2 peaks (the higher one at the end of the season) was evident. Figures 4j-4n, showing *Quercus* pollen curves in Southern Spain, indicated high pollen counts, with several peaks during the season.

**Daily pollen forecasting.** Spearman's correlation test detailed results are not shown, due to their length and similarity to regression results. They revealed that temperature was the main factor affecting daily pollen concentrations at all sites. The correlation with temperature was positive in the Pre-Peak period, but negative in the whole-season analysis. These results were particularly evident at sites with longer pollen seasons. Moreover, the correlation analysis of pollen vs. wind data showed significant positive correlation coefficients at coastal sites on days when the wind came from inland; in contrast, the wind coming from the ocean prompted a decrease in airborne pollen. Similarly, in inland areas where *Quercus* pollen is influenced by the effect of valley-mountain winds, or where *Quercus* populations are

located quite far from the monitoring site, wind direction and intensity also influenced pollen counts. Regression equations for many sites showed that daily temperature also exerted a positive effect on pollen data in the Pre-Peak period, while the results for the After-Peak period show that humidity and rainfall has a negative effect on airborne pollen. Moreover, previous pollen counts are more effective forecasting variables in the After-Peak period (Tabs. 3, 4). Fewer year-on-year differences were observed at coastal sites than in inland regions.

**Validation of daily pollen forecasts.** Most of the proposed daily pollen forecasting models recorded significant statistical coefficients (Tabs. 3, 4). Nevertheless, models were externally validated for 2001 and 2004, both graphically and statistically. Figure 5 shows the expected vs. observed daily pollen values in 2001 and 2004 for each site. Grey lines represent actual data and black lines represent expected data. Wider line represents 2001 data. The $R^2$ coefficient and the Wilcoxon matched pair test results from the statistical validation are shown in Table 5, p values > 0.01 indicate non-significant differences. The acceptable statistical results and similar patterns of the curves suggested that main daily pollen characteristics, such as the increase, peak or decrease periods, can be forecasted using the proposed equations.

**Pollen Index forecasting.** Annual Pollen Index (PI) at most sites were very high compared to pollen emitted by most of the anemophilous species presented in the study sites, particularly those detected in the Mediterranean area (Fig. 6). The Atlantic sites located in NW Spain had the lowest *Quercus* PI; higher amounts were recorded at
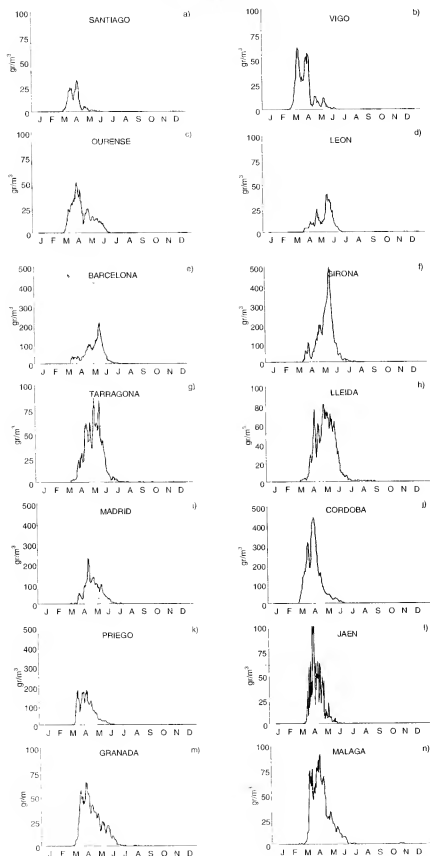
**Figure 4.** Average *Quercus* pollen season curves during 1992-2004 at the different sites. In the Y axis is represented the concentration of pollen expressed as grains per cubic meter (gr/m³).

**Table 3.** Daily pollen forecasting equations from localities that suffered the drought period (1992-1995).

| | | |
|---|---|---|
| BARCELONA 94-95 | Pre R² 0.36 p<0.00 | QUER: -9.9+0.17Q2+0.98Tmx |
| | After R² 0.49 p<0.00 | QUER: 20.08+0.11Q2-0.94Rf-0.83Rf-0.83Tmn |
| LEON 94-95 | Pre R² 0.82 p<0.00 | QUER: 26.76+7.19WF3+3.85Rf1+2.17WF1 |
| | After R² 0.53 p<0.00 | QUER: 28.3+0.27Q1-0.29H+0.32Rf1-0.24Tmx2 |
| MADRID 93-95 | Pre R² 0.56 p<0.00 | QUER: -61.18+6.33Tmn2+0.31Q1+1.17S5 |
| | After R² 0.75 p<0.00 | QUER: 13.5+0.41Q2-0.23Q1-0.16Q3+0.43H3-0.58Tmn2 |
| CORDOBA 93-95 | Pre R² 0.68 p<0.00 | QUER: -61.18+6.33Tmn2+0.31Q1+1.17S5 |
| | After R² 0.60 p< 0.00 | QUER: -108.19+0.68Q1+1.6WF3-1.16WF1 +2.18S2 |
| PRIEGO 94-95 | Pre R² 0.89 p<0.00 | QUER: -231.2+2.05Q1+46.7WF4+4.1S3 |
| | After R² 0.70 p<0.00 | QUER: 71.24+0.47Q1+0.14Q3-0.52H-1.5Tmn2 |
| GRANADA 92-95 | Pre R² 0.75 p<0.00 | QUER: -14.4+0.54Q1+1.27Tmx1+0.11Q2 |
| | After R² 0.73 p<0.00 | QUER: 40.9+0.19Q2+0.29Q1-0.48H-0.84Tmn |
| MALAGA 92-95 | Pre R² 0.70 p<0.00 | QUER: -192.7+0.178Q3+6.21Tmed+0.11Q2 |
| | After R² 0.77 p<0.00 | QUER: 40.9+0.2Q2+0.3Q1+1.6WV-3.48Tmx +0.34WF4 |
| JAEN 96-00 | Pre R² 0.65 p<0.00 | QUER: -70.9+1.14Q1+20.4WF1+9.55WF4 -16.78Rf |
| BARCELONA 96-00 | Pre R² 0.57 p<0.00 | QUER: -17.9+0.24Q2+3.84Tmn2-1.63Rf |
| | After R² 0.52 p<0.00 | QUER: 254.19+0.98Q1-0.73Q3+0.68Q2 -2.8Tm-22.8S |
| LEON 96-00 | Pre R² 0.67 p<0.00 | QUER: -48.65+0.18Q3+3.14Tmx+0.09Q2 -0.13WV4 |
| | After R² 0.82 p<0.00 | QUER: 7.98+0.15Q3-0.25Q1-0.43WV +0.66H-0.33Tmx2 |
| MADRID 96-00 | Pre R² 0.71 p<0.00 | QUER: 4.8+0.51Q1+0.59Q2-0.6WF4 +3.9S1 |
| | After R² 0.49 p<0.00 | QUER: 99.2+0.25Q1+0.08Q3-4..5Tm2+0.03Q2 |
| CORDOBA 96-00 | Pre R² 0.75 p<0.00 | QUER: 432.9+0.8Q2-6.4H+9.9WV -8.4WF2 |
| | After R² 0.59 p<0.00 | QUER: 42.18+0.6Q1-14.6Tm |
| PRIEGO 96-00 | Pre R² 0.94 p<0.00 | QUER: 3.68+0.72Q1-1.6Q2 |
| | After R² 0.83 p<0.00 | QUER: -70.5+0.72Q1-0.15Q2-6.44Tmn1 |
| GRANADA 96-00 | Pre R² 0.81 p<0.00 | QUER: -148.09+2.32Q2+0.82WC3+3.33Tmx2 |
| | After R² 0.65 p<0.00 | QUER: 75.39+0.39Q1-0.9Tmn-0.79H -0.74Tmn2 |
| MALAGA 96-00 | Pre R² 0.55 p<0.00 | QUER: -305.8+0.6Q2+19.1Tmx-0.2Q3 +15.8Tmx1+4.2WF1 |
| | After R² 0.41 p<0.00 | QUER: 77.4+0.25Q2-3.05Tmn2-0.3WF2 -2.23Rf |
| JAEN 96-00 | After R² 0.55 p<0.00 | QUER: 25.6+0.42Q1-0.19H-3.4H1 |

Pre - Pre-Peak Season, Quer - *Quercus* pollen , Tmx - Maximum Temperature, Tm - Mean Temperature, WFn - Wind Frequency, n quadrant, Tmin - Minimum temperature. S - Sunshine Hours, Rf - Rainfall (mm), After - After-Peak season, Q - *Quercus* pollen , H - Relative Humidity, WV - Wind Velocity (km/h), C - Wind Calm, Index 1 - Data from the previous day, Index 2, 3, ... - Cumulated data from the two, three, ... previous days, gr/m³ - Pollen grains by cubic meter.

Central and Southern sites. Regression analysis showed that rainfall and temperature (particularly maximum temperature) were the most important variables in Mediterranean areas, while both maximum and minimum temperatures prior to flowering were the most important parameter in Eurosiberian areas. There was a geographical gradient with respect to the months with the greatest influence in the forecast. Meteorological conditions 1 month prior to the pollen season had a decisive effect on models (Tab. 7).

**Validation of Pollen Index forecasting.** All regression models showed an adjusted regression coefficient (R²) close to 1, with a probability value from 95-100% (Tab. 7). In Table 6, the plotting of actual vs. expected data from the validation in 2001 and 2004 yielded good results, with a Root Mean Square Error between actual and expected values of 16.2 in 2001 and 21.4 in 2004. An acceptable error under 25% was generally found. The difference was considerably smaller for Vigo, Ourense, Madrid, Cordoba, Granada and Malaga.

**Climate Change model simulation.** The average 4°-5°C rise in temperature produced by expected global warming prompted an increase in modelled flowering. Although the model did not predict significant changes in rainfall in the Iberian Peninsula, a increase of 5-10% in annual rainfall may occur in the Mediterranean area. This increase would be registered by means of more torrential rainfall episodes alternating with higher drought periods. The rate of future climate change simulated by the RCM varied significantly among Iberian areas (Fig. 1). Expected changes in temperature and rainfall could prompt a marked geographical variation in pollen production for *Quercus* species. The use of meteorological parameters for 2025, 2050, 2075 and 2099 in the validated Pollen Index forecasting models indicated that *Quercus* pollen production in the Iberian Peninsula could become significantly higher at most study sites (Tab. 8). The range of variation in PI as a function of the mean PI value (Pollen Index/Mean Pollen Index) is shown for the last decade. *Quercus* pollen production would record the maximum increase between 2050-2075, while few differences are
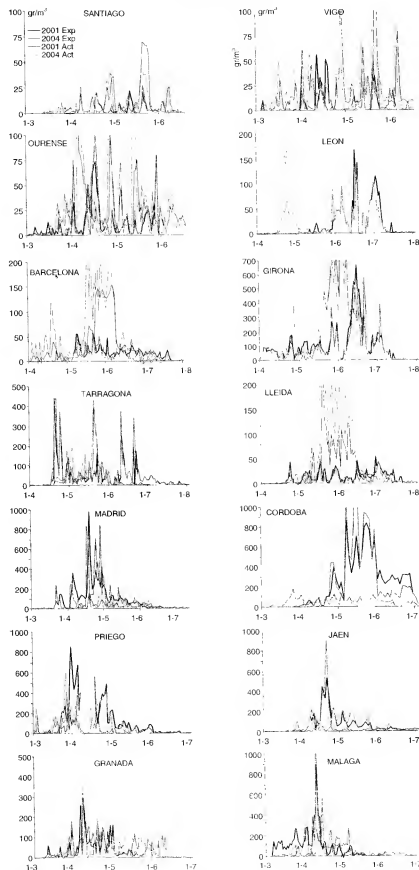
**Figure 5.** Daily pollen forecast validation for 2001 and 2004 (not included in the models) gr/m³ pollen grains by cubic meter. Grey line: actual data; black line: expected data. Dates are represented in x-axe.
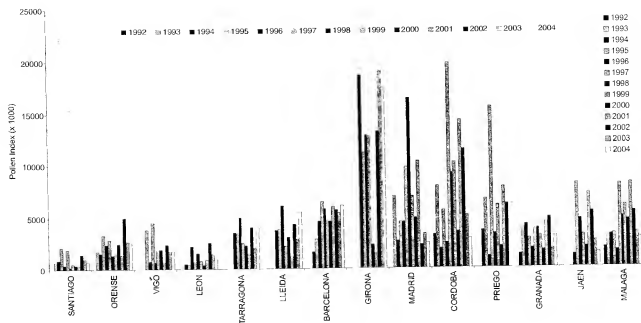
**Figure 6.** Evolution of annual *Quercus* Pollen Index in study areas.

expected for the last 25 years of the 21st century. Comparison with the variation factor expected in the future (Future Pollen Index/Mean Pollen Index) shows that expected PI will increase two and a half-fold from today's values. Climate simulation for the doubled $CO_2$ scenario produced different rates of pollen increase in different areas; these were lower in coastal areas than at inland sites, Mediterranean inland areas being the most affected.

## DISCUSSION

Understanding pollen emission dynamics is fundamental for the characterization of potential allergens that may be of greater health relevance in both natural spaces and populated areas. *Quercus* airborne pollen counts at a given sampling station reflect reproductive phenology over an extended area [30]. Taking into account the number and distribution of the sites studied in the present paper, this research provides valuable information on the

pollination dynamics features of *Quercus* genus in the Iberian Peninsula. The present results could be very useful for allergy physicians to know the main meteorological factors influencing on *Quercus* pollination dynamics. Moreover, the investigations carried out on the possible future consequences of climate change can give them a new vision of the possible changes in atmospheric allergens occurrence.

Results indicate that *Quercus* pollen season start has been advancing over recent years in the Iberian Peninsula. Results were similar to those obtained in a previous study involving fewer sites and years [27]. Other authors in northern Europe have reported similar findings for the *Quercus* pollen season [9]. With regard to other species, a progressive advance in flowering has also been observed in *Betula* [17], Poaceae [18], and *Alnus* and *Olea* [11] over the last 20 years. All these findings indicate that spring phenology in Europe is being significantly affected by global warming. On the basis of previous studies [26,

**Table 4.** Daily pollen forecasting equations from the north-west localities that did not suffer the drought period (Santiago, Vigo and Ourense). Results from localities with a shorter data base, (Girona, Lleida and Tarragona) also shown.

| | | |
|---|---|---|
| SANTIAGO 93-00 | Pre $R^2$ 0.84 p<0.00 | QUER: -26.9+0.56Q1+0.4Q3+1.9Tm1+1.8Tmx1 |
| | After $R^2$ 0.81 p<0.00 | QUER: 46.7+0.51Q1-0.41H-0.32C+0.51Tmx2 |
| VIGO 95-00 | Pre $R^2$ 0.83 p<0.00 | QUER: -7.69+0.38Q2+0.30Q1-0.9WF3-1.59S2+2.7Tmx2 |
| | After $R^2$ 0.68 p<0.00 | QUER: 7.61+0.28Q1-2.1WF1+0.05Q3-1.46WF4-0.29Rf3 |
| OURENSE 93-00 | Pre $R^2$ 0.84 p<0.00 | QUER: -26.9+0.72Q1+1.5Tmx+0.9S |
| | After $R^2$ 0.81 p<0.00 | QUER: 9.8+0.50Q1-0.09H-0.32Tmn1-0.37Tmx2 |
| GIRONA 96-00 | Pre $R^2$ 0.69 p<0.00 | QUER: -168.11+1.07Q1+15.39Tm-0.33Q2 |
| | After $R^2$ 0.73 p<0.00 | QUER: 94.2+0.71Q1+0.14Q2-2.5Tmn2-1.2S2+1.08WV |
| LLEIDA 96-00 | Pre $R^2$ 0.54 p<0.00 | QUER: -207.5+0.89Q1+9.68Tmx+2.88P1 |
| | After $R^2$ 0.51 p<0.00 | QUER: 12.49+0.58Q1-3.6Tmn1-0.08Tmx+1.72Rf3 |
| TARRAGONA 96-00 | Pre $R^2$ 0.53 p<0.00 | QUER: -44.04+6.46Tmn+0.41Q1+5.93Tmn1 |
| | After $R^2$ 0.52 p<0.00 | QUER: 19.86+0.59Q1+0.59Rf1-0.35H+0.19H1 |

Table 5. Daily pollen forecast validation for 2001 and 2004. $R^2$ and Wilcoxon pair test results shown. Differences significant at p<0.01.

| Site | Year | $R^2$ | Wilcoxon Matched Pairs Test* | | | |
|---|---|---|---|---|---|---|
| | | | N | T | Z | p level |
| Santiago | 2001 | 0.55 | 59 | 160.50 | 1.23 | 0.21 |
| | 2004 | 0.68 | 122 | 598.00 | 1.24 | 0.21 |
| Vigo | 2001 | 0.72 | 116 | 214.00 | 1.42 | 0.15 |
| | 2004 | 0.46 | 107 | 1,306.00 | 2.85 | 0.00 |
| Ourense | 2001 | 0.77 | 116 | 1,097.00 | 1.73 | 0.08 |
| | 2004 | 0.65 | 115 | 2,116.50 | 0.77 | 0.44 |
| Leon | 2001 | 0.74 | 91 | 216.00 | 1.83 | 0.66 |
| | 2004 | 0.72 | 81 | 359.00 | 2.85 | 0.00 |
| Barcelona | 2001 | 0.68 | 122 | 515.50 | 1.58 | 0.11 |
| | 2004 | 0.64 | 106 | 930.00 | 1.83 | 0.07 |
| Girona | 2001 | 0.73 | 121 | 857.50 | 3.65 | 0.03 |
| | 2004 | 0.80 | 113 | 1,306.00 | 0.24 | 0.81 |
| Tarragona | 2001 | 0.53 | 122 | 970.00 | 2.40 | 0.02 |
| | 2004 | 0.83 | 92 | 545.50 | 1.23 | 0.26 |
| Lleida | 2001 | 0.40 | 122 | 1,284.00 | 3.20 | 0.01 |
| | 2004 | 0.61 | 106 | 1,337.50 | 1.68 | 0.09 |
| Madrid | 2001 | 0.27 | 123 | 1,201.00 | 2.00 | 0.04 |
| | 2004 | 0.34 | 122 | 2,224.50 | 0.38 | 0.71 |
| Cordoba | 2001 | 0.78 | 85 | 601.00 | 1.21 | 0.22 |
| | 2004 | 0.65 | 98 | 1,306.00 | 2.33 | 0.08 |
| Priego | 2001 | 0.58 | 112 | 1,309.00 | 5.00 | 0.01 |
| | 2002 | 0.45 | 77 | 1,099.50 | 1.55 | 0.12 |
| Jaen | 2001 | 0.79 | 91 | 783.00 | 1.16 | 0.24 |
| | 2004 | 0.23 | 104 | 184.00 | 4.14 | 0.00 |
| Granada | 2001 | 0.79 | 127 | 1,033.00 | 0.05 | 0.96 |
| | 2004 | 0.43 | 119 | 493.00 | 1.97 | 0.06 |
| Malaga | 2001 | 0.52 | 131 | 1,407.00 | 1.53 | 0.13 |
| | 2004 | 0.40 | 115 | 2,839.00 | 0.64 | 0.52 |

* Marked differences are significant at p<0.05

Table 6. Annual Pollen Index forecast validation for 2001 and 2004. The Expected (Exp) and Actual (Act) Pollen Index (PI), and difference between them are shown. The fifth column indicates the percentage of error (%Error) in relation with the actual Pollen Index. The Absolute Mean, Standard Deviation (SD) and Root Mean Square Error (RMSE) are also shown.

| Site | Year | Expected PI | Actual PI | Dif (Exp-Act) | %Error |
|---|---|---|---|---|---|
| Santiago | 2001 | 209 | 282 | -73 | 25 |
| | 2004 | 792 | 685 | 107 | 15 |
| Vigo | 2001 | 520 | 629 | -109 | 17 |
| | 2004 | 1,972 | 1.742 | -230 | 1 |
| Ourense | 2001 | 1,386 | 1,387 | -1 | 0.07 |
| | 2004 | 2,168 | 2,578 | 410 | 15 |
| Barcelona | 2001 | 2,424 | 5,965 | -3,541 | 59 |
| | 2004 | 4,289 | 6,002 | -1,713 | 28 |
| Tarragona | 2001 | 1,410 | 1,412 | -2 | 0.14 |
| | 2004 | 2,647 | 3,931 | -1,284 | 32 |
| Girona | 2001 | 1,837 | 1,411 | 426 | 30 |
| | 2004 | 20,933 | 19.113 | -1,820 | 9 |
| Lleida | 2001 | 1,122 | 1,119 | 3 | 0.26 |
| | 2004 | 3,225 | 5,429 | -2,204 | 40 |
| Leon | 2000 | 1,197 | 822 | -375 | 41 |
| | 2004 | 1,244 | 1,405 | -161 | 11 |
| Madrid | 2001 | 12,564 | 10,307 | 2,257 | 19 |
| | 2004 | 2,422 | 2,525 | 103 | 4 |
| Cordoba | 2001 | 13,324 | 14,260 | -936 | 6.5 |
| | 2004 | 2,990 | 2,891 | -99 | 3 |
| Priego | 2001 | 8,024 | 7,774 | -250 | 3 |
| | 2002 | 4,272 | 6,158 | -1,886 | 30 |
| Jaen | 2001 | 5,931 | 7,161 | -1,230 | 17 |
| | 2004 | 896 | 1,931 | -1,035 | 50 |
| Granada | 2001 | 5,235 | 4,429 | 806 | 17 |
| | 2004 | 3,992 | 4,303 | -311 | 7 |
| Malaga | 2001 | 6,224 | 8,156 | -1,932 | 23 |
| | 2004 | 3,195 | 2,823 | 372 | 13 |
| Absolute Mean | 2001 | | | 852 | 17.4 |
| | 2004 | | | 838 | 18.4 |
| SD | 2001 | 4,367 | 4,372 | | |
| | 2004 | 5,026 | 4,565 | | |
| RMSE | 2001 | | | 16.2 | |
| | 2004 | | | 21.4 | |

27] it is clear that the *Quercus* start date in the Iberian Peninsula is strongly determined by temperature, therefore, if our climate continues to change as projected, the start of the *Quercus* pollen season would continue to advance.

Comparative aerobiological studies of sites with different climatic characteristics give us a global idea of the different behaviour of airborne pollen under specific meteorological conditions in large areas [19]. Regarding *Quercus* daily pollen dynamic in Spain, the seasonal floral phenology of the various *Quercus* species presented at each site determines the shape of the pollen curve. The curve was fairly similar for the 3 study sites in the NW area: Santiago, Vigo and Ourense. In Southern Spain, the 3 species present in lower altitude areas (Cordoba and Malaga). *Q. ilex* subsp. *ballota*, *Q. coccifera* and *Q. suber* have consecutive flowering periods that gave rise to a 3-peak pattern, the highest being the *Q. ilex* subsp. *ballota* peak. In higher altitude areas, such as Jaen, Granada and Priego, the great abundance of *Q. ilex* subsp. *ballota* accounted for almost all pollen grains reflected in the curve. In these areas, *Q. ilex* subsp. *ballota* populations growing at different altitudes caused consecutive peak pollination patterns; in this case, topography was responsible for the irregular curve.

The specific aerobiological behaviour of *Quercus* pollen has been studied in different parts of Europe and the USA from a descriptive standpoint [9, 25, 35, 37, 50]. However, no studies have been performed on the forecasting of airborne *Quercus* pollen levels. The daily forecasting results presented here indicate that the main variables were temperature and hours of sunshine, with a

**Table 7.** Annual Pollen Index (PI) forecasting regression equations.

| Site | Regression equation | R² | p level |
|---|---|---|---|
| Santiago | PI=-22885+19(RfF1)+460(MeanF2)+1086(MxJ2)+270(MxJ1) | 0.99 | 0.02 |
| Vigo | PI=11345+4(RfJ2)+1610(MnF2)+434(MnJ2)-1652(MxF2) | 0.99 | 0.02 |
| Ourense | PI=2905+5.4(RfJ1)+3.6(RfJ2)+(MnF1)-274(MnJ1)-238(MeanF2) | 0.99 | 0.03 |
| Barcelona | PI=4401-61(RfF1)+28(RfJ2)-150(RfZ) | 0.99 | 0.00 |
| Tarragona | PI=36344-2423(MxF2)+228(RfF1) | 0.99 | 0.00 |
| Girona | PI=35221-2023(MxM1)+1238(MeanF2)-76(RfJ1)+40(RfJ2) | 0.99 | 0.00 |
| Lleida | PI=5075-45(MxM1)-139(MnM1)-121(RfM1)+205(RfF1) | 0.99 | 0.00 |
| Leon | PI=9047-888(MxJ2)+8(MxF2)+5.3(RfF1) | 0.98 | 0.00 |
| Madrid | PI=-26098+1955(MnF1)+3909(MnM1)+996(MeanJ1)+1005(MeanJ2) | 0.99 | 0.02 |
| Cordoba | PI=32909+1652(MxF2)+1082(MeanF1)+100(RfF1)+415(MnE2) | 0.98 | 0.00 |
| Priego | PI=757+1367(MnF2)+52(RfF2) | 0.99 | 0.01 |
| Jaen | PI=-37045-3571(MeanM1)+6664(MnM1)+2391(MxJ1) | 0.99 | 0.02 |
| Granada | PI=3731-1002(MeanF1)+1002(MnF1)-64(RfM1)-21(MeanF2)+10.6(RfJ1)-170(MeanJ1) | 0.99 | 0.05 |
| Malaga | PI=5576+648(MxF2)+9.4(RfJ1)+409(MeanF2)+303(MxM1) | 0.99 | 0.00 |

RfJ - Rainfall January , RfF - Rainfall February , RfM - Rainfall March , MxJ - Maximum Temperature January, MxF - Maximum Temperature February, MxM - Maximum Temperature March, Index 1 - 1st fortnight, MeanJ - Mean Temperature January, MeanF - Mean Temperature February, MeanM - Mean Temperature March, MnJ - Minimum Temperature January, MnF - Minimum Temperature February, MnM - Minimum Temperature March, Index 2 - 2nd fortnight.

**Table 8.** Average Pollen Index (PI) from last years (1992-2004) compared with the calculated future PI at different sites of the Iberian Peninsula. Range and average value of variation factors from the last decade is compared with the adjusted increase factor expected for the end of the 21st century.

| Site | Last decade Mean Pollen Index (MPI) | Last decade Range of Variation Factor (PIn/MPI) | Last decade Average Variation Factor | PI 2025 | PI 2050 | PI 2075 | PI 2099 | Variation Factor (PI 2099/MPI) |
|---|---|---|---|---|---|---|---|---|
| Santiago | 825 | (0.3-2.5) | 1.4 | 870 | 870 | 880 | 880 | 1.1 |
| Vigo | 2,044 | (0.4-2.2) | 1.3 | 2,100 | 2,100 | 2,200 | 2,250 | 1.1 |
| Ourense | 1,500 | (0.9-2.2) | 1.5 | 2,050 | 5,600 | 9,650 | 10,800 | 7.2 |
| Barcelona | 4,500 | (0.4-1.2) | 0.8 | 5,100 | 5,900 | 6,200 | 6,100 | 1.4 |
| Tarragona | 3,000 | (0.7-1.4) | 1.05 | 3,510 | 4,100 | 4,650 | 4,640 | 1.5 |
| Girona | 9,850 | (0.2-1.7) | 0.95 | 10,530 | 13,730 | 14,800 | 15,410 | 1.5 |
| Lleida | 3,500 | (0.4-1.7) | 1.05 | 5,080 | 7,550 | 7,900 | 8,000 | 2.3 |
| Leon | 900 | (0.5-2.3) | 1.4 | 2,500 | 3,740 | 3,970 | 4,100 | 4.5 |
| Madrid | 7,500 | (0.4-2.0) | 1.2 | 9,000 | 16,750 | 21,200 | 23,800 | 3.2 |
| Cordoba | 8,000 | (0.3-2.3) | 1.3 | 11,210 | 16,600 | 23,500 | 24,500 | 3.1 |
| Priego | 6,000 | (0.3-2.4) | 1.35 | 6,400 | 10,500 | 17,320 | 17,600 | 3.0 |
| Jaen | 4,400 | (0.3-1.8) | 1.05 | 6,500 | 7,540 | 8,500 | 9,800 | 2.2 |
| Granada | 3,200 | (0.5-1.3) | 0.9 | 4,870 | 5,600 | 5,600 | 5,600 | 1.8 |
| Malaga | 5,000 | (0.4-1.6) | 1 | 5,090 | 5,500 | 6,210 | 6,600 | 1.3 |
| Absolute Mean | 4,300 | (0.4-1.9) | 1.16 | 5,340 | 7,580 | 9,470 | 10,005 | 2.5 |

MPI - Mean Pollen Index, PI - Pollen Index, PIn - Pollen Index from each study year.

positive effect on daily *Quercus* pollen variation. It was noticeable that at many sites, daily temperature variables showed positive coefficients in the Pre-Peak equations, whereas previous results for the whole season displayed significant negative coefficients. The extensive length of the *Quercus* pollen season makes coincide the increase in temperature in late spring/early summer with the end of the season, when decreasing pollen concentrations were recorded due to the intrinsic phenology of the plants. Due to this fact, different meteorological factors influenced in the 2 pollination periods. Results showed that different meteorological factors affected in the 2 periods. In the Pre-Peak period, temperature variables positively affect the pollen liberation, whereas in the After-Peak period, Humidity and Rainfall influence the atmospheric dynamics of the pollen already liberated.

Moreover, the use of previous pollen records has proved to be a very useful tool in pollen forecasting overall in the After-Peak period. The use of this sort of data is recommended in taxa with a recurrent pollen curve year after year, such as *Quercus* [6, 43]. In general, the validation of the proposed models was performed in 2 years in order to confirm the results. The years from 2001-2004 were climatically similar to the 1996-2000 period, and drought years were not detected. 2001 and 2004 years were randomly chosen. Validation of the daily forecast models for 2001 and 2004 showed that the main daily pollen characteristics can be accurately forecasted.

A number of authors have studied inter-annual Pollen Index variations in different species in broad geographic zones, such as all Europe [55], England [18], Italy [21] and the Iberian Peninsula [25, 34]. In general, these authors reported that bio-geographic and climatic characteristics, as well as human action, can affect air-borne pollen counts in each area. In the present study, the highest pollen concentrations were detected in different years, depending on the area, although fewer inter-annual differences in pollen counts were observed at coastal sites than in inland study areas; this may have been due to the lower degree of climate variation in these areas. In general, the annual PI tended to decrease in the early years of sampling (1992-1995) due to the drought. Later, annual PI increased due to recovery of these trees. Nevertheless, this recovery was not detected in the first "post-drought" year (1996) as might be expected, but 2 years later, in 1997. The extreme drought period weakened oaks, slowed down vegetative growth, and prompted biomass loss. The wetter 1995-1996 winter probably led to a recovery of vegetative biomass and to strong production of vegetative buds instead of floral structures. This phenomenon was clearer in the south of the Peninsula, where the shortage of rain was most acute. The same trend has been observed in other species in the Peninsula, such as *Olea europaea* [13] or *Platanus* spp. [14].

In 1997, 1998, 2003 and 2004 the highest PI was recorded in the southern cities, whereas in the northwest area – unaffected by the drought – the highest concentrations were detected in 1995. During this year, a very high concentration of *Quercus* pollen was also observed in England [9]. Weather conditions over previous months have been shown to exert a remarkable effect on the intensity of *Quercus* flowering. Rainfall during the month prior to the pollen season has been highlighted as the parameter making the greatest contribution to pollen production. In other species, such as the olive which flowers in late spring, studies report that in Cordoba (southern Spain) rains make the greatest contribution to flower production in March [23], whereas in Perugia (Central Italy) the rain effect on flowering intensity is strongest in May [20]. In the Cupressaceae family which flowers in winter, it has been reported that the minimum temperature in November and rainfall in November and December were the variables exerting the

greatest influence on the PI [22]. In other models designed for trees with clear biennial patterns, such as *Betula*, PI values from the previous year have been included as independent variables, as well as temperatures in the current year [12]. In the results obtained here, the variables with greatest influence on total *Quercus* pollen counts were rainfall and maximum temperature in Mediterranean localities, and minimum temperatures in Eurosiberian Region sites or those influenced by its climate. This may be due to the fact that Mediterranean species flower during early spring when minimum temperatures do not vary significantly from winter, whereas Eurosiberian species flower in late spring when minimum temperatures are much higher and go a long way towards determining the development of floral structures. The gradients for the most influential months, i.e. weather characteristics 1 month prior to flowering, have the strongest influence on oak flowering intensity.

In Spain, 21.5% of the population suffer from pollen allergy which involves a high number of sick leaves [2]. Annual allergy costs for the Spanish Government rise above 1,500 million Euros [39]. Advance knowledge on the intensity of the pollen season would help allergy physicians and allergy sufferers to better plan and manage allergy treatments.

Prentice *et al.* [49] examined the implications for future $CO_2$ concentrations. Projected increase in $CO_2$ concentration by 2099 ranged from 1.9-3.5 times. Nevertheless, the most expected $CO_2$ increase is projected to rise 2 times [10]. The implementation of future climate data presented in this work was carried out under x2 $CO_2$ scenario. Results indicate that the *Quercus* species in the Iberian Peninsula are already responding to climate warming. Changes in temporal occurrence of atmospheric allergens could have important clinical consequences [3]. The floral phenology of *Quercus* species in the Iberian Peninsula is suffering the rising spring temperatures in the Mediterranean area, like the phenology of *Betula* and *Alnus* in colder biomes, where climatic warming is already having a visible impact on vegetation [8, 16, 41, 54]. Moreover, floral phenology of other tree species in the Iberian Peninsula is being affected. It has been detected that *Olea* flowering season has suffered a general advance in the Iberian Peninsula [24]. This advance has been shorter than that observed for *Quercus* species, probably due to the higher dependency on temperature of early spring tree species flowering date. For late spring species, such as olive, photoperiod and rainfall also influence the flowering date [24]. The increase of temperature is probably affecting the flowering of many other Iberian species, especially species like *Platanus* or *Ulmus*, which have shown a clear response to temperature before flowering [1]. Modelling future Ombrothermal Indexes combining Temperature, Rainfall, Aridity and Continental Indexes for the inland central area of Leon suggest that the next 50 years will not see significant changes in seasonal rainfall distribution – a major factor for climate-related plant species [51]. The study also

predicts an increase in temperature of 1-2°C over the next 50 years, which will lead to accelerated vegetative and flower growth and an advance in flowering dates. The results of that local study agree with those reported here for the Leon area.

A number of authors have reported that the increase in airborne pollen counts recorded by most European aerobiology stations over recent years may be due to this climate warming [33, 47]. Some authors, using a vegetation biogeochemical model (BIOME3) where torrential rainfall increases 5-10% in the Mediterranean area, indicated that future climate conditions will lead to the spread of an evergreen forest in the Mediterranean [7, 31]. This hypothesis, taken in conjunction with the models proposed here, suggests an increase in the evergreen *Quercus* pollen of the Iberian Peninsula. The pollen season of these trees will start earlier, and will also prompt higher pollen emissions throughout the Mediterranean area. These effects would be more evident in inland areas as Madrid, Leon, Jaen or Cordoba.

The present paper, together with other studies performed in different anemophilous species, show considerable evidence to suggest that climate change, specially temperature increase, will have, and has already had, impacts on aeroallergens. Climate change effects include impacts not only on pollen amount and pollen season, but also in plant and pollen distribution and other plant attributes. For this reason, theoretical models, such as these here presented, must be understood only as a partial approach to the future environmental conditions that could also be modified by deforestation, or land use changes. There are many research challenges to a more complete understanding of the impacts of climate change on aeroallergens and allergic diseases [3]. In-depth studies covering main allergenic pollen species in Europe should be carried out in order to obtain a full idea of the possible effect of climate change on the pollination dynamic characteristics. Therefore, new efforts on this subject should be made by public health authorities and allergy physicians in order to be aware of these changes in the environment to adapt allergy treatments.

## CONCLUSIONS

*Quercus* floral phenology has been advancing over the last few years; pollen seasons in the Iberian Peninsula have, since the beginning of the 90s, been starting an average of 2 weeks earlier.

*Quercus* pollen-curve characteristics varied between different bio-geographical zones, but were similar for sites with similar climate and species. It was therefore possible to distinguish 4 general patterns in the NW, NE, Central, and Southern areas. In the Mediterranean area, minimum and maximum temperatures were the main parameters influencing daily pollen-count. Maximum temperature was the most influential factor in the Euroiberian area.

The Pollen Index varied considerably between sites and years, depending on previous weather conditions. In the

Mediterranean area, rainfall and temperature (particularly maximum temperature) prior to flowering were the most important variables. Both maximum and minimum temperatures were the major parameters in the Euroiberian area.

Results of external validation of daily and annual forecasting models suggest the possibility to use *Quercus* pollen forecasts in future in the Iberian Peninsula.

Using the RCM climate-change model, it may be suggested that the impact of future climate variation on Iberian *Quercus* floral phenology would be different depending on the areas. It would be more marked in inland than in coastal areas. In general, the pollen season will start earlier and will also prompt higher pollen emissions throughout the inland Mediterranean area in general. Thus, the likelihood is that climate change will modify the time of the occurrence of human oak-pollen-allergy problems.

Using climate predictions from the RCM climate, our results would suggest that, as climate warms, the Iberian *Quercus* pollen season will start earlier and will also prompt higher pollen emissions, with the strongest effects in inland areas. Therefore, the likelihood is that climate change will intensify human oak-pollen-allergy problems.

## REFERENCES

1. Alba F, Díaz de la Guardia C: The effect of air temperature on the starting dates of the *Ulmus*, *Platanus* and *Olea* pollen season in the SE Iberian Peninsula. *Aerobiologia* 1998, **14**, 191-194.
2. Bauchau V, Durham SR: Prevalence and rate of diagnosis of allergenic rhinitis in Europe. *Eur Respir J* 2004, **24**, 758-764.
3. Beggs PJ: Impacts of climate change on aeroallergens: past and future. *Clin Exp Allergy* 2004, **34(10)**, 1507-1513.
4. Bradley NL, Leopold AC, Ross J, Huffaker W: Phenological changes reflect climate change in Wisconsin. *Proc Natl Acad Sci USA* 1999, **96**, 9701-9704.
5. Butland BK, Strachan DP, Lewis S, Bynner J, Butler N, Britton J: Investigation into the increase of hay fever and eczema at age 16 observed between the 1958 and 1970 British birth cohorts. *Br Med J* 1997, **315**, 717-721.
6. Comtois P, Sherknies D: Le pollen de l'Ambroisie (*Ambrosia artemisiifolia* L): previsions et préventions. *Aller Immunol* 1992, **24**, 22-26.
7. Cheddadi R, Guiot J, Jolly D: The Mediterranean vegetation: what if the atmospheric CO₂ increased? *Landscape Ecol* 2001, **16**, 667-675.
8. Chmielewski FM, Rötzer T. Response of tree phenology to climate change across Europe. *Agric Forest Meteorol* 2001, **108**, 101-112.
9. Corden J, Millington W: A study of *Quercus* pollen in the Derby area, UK. *Aerobiologia* 1999, **15**, 29-37.
10. Cubash U, Meehl GA, Boer GJ et al.: Projections of future climate change. **In**: Houghton JT, Ding Y, Griggs DJ, Noguer M, Van der Linden PJ, Dai X, Maskell K, Johnson CA (Eds). *Climate Change 2001: The Scientific Basis. Contribution of Working Group of the IPCC.* 525-582. Cambridge, University Press Cambridge 2001.
11. D'Odorico P, Yoo J, Jaeger S: Changing seasons: an effect of the North Atlantic Oscillation? *J Clim* 2002, **15**, 435-445

12. Dahl A, Strandhede S: Predicting the intensity of the birch pollen season. *Aerobiologia* 1996, **12**, 97-106.

13. Díaz de la Guardia C, Galán C, Domínguez E, Alba F, Ruíz L, Sabariego S, Recio M, Fernández-González D, Méndez J, Vendrell M, Gutiérrez M: Variations in the main pollen season of the *Olea europaea* L. at selected sites in the Iberian Peninsula. *Polen* 1999, **10**, 103-113.

14. Díaz de la Guardia C, Galán C, Domínguez E, Alba F, Ruíz L, Sabariego S, Recio M, Fernández-González D, Méndez J, Vendrell M, Gutiérrez M: Aeropalynological study of the genus *Platanus* L. in the Iberian Peninsula. *Polen* 1999, **10**, 93-101.

15. Domínguez E: The Spanish Aerobiology Network (REA). *Aerobiologia* 1992, **8(2/1)**, 45-46.

16. Emberlin J: The effects of patterns in climate and pollen abundance on allergy. *Allergy* 1994, **49**, 15-20.

17. Emberlin E, Mullins J, Corden J, Millington W, Brooke M, Savage M, Jones S: The trend to earlier birch pollen seasons in the UK: A biotic response to changes in weather conditions? *Grana* 1997. **36**, 29-33.

18. Emberlin J, Jaeger S, Domínguez E, Galán C, Hodal L, Mandrioli P, Rantio-Lehtimäki A, Savage M, Spieksma FTh, Barlett C: Temporal and geographical variations in grass pollen seasons in areas of western Europe: an analysis of season dates at sites of the European pollen information system. *Aerobiologia* 2000, **16**, 373-379.

19. Emberlin J, Mullins J, Corden J, Jones S, Millington W, Brooke M, Savage M: Regional variations in grass pollen seasons in the UK, long-term trends and forecast models. *Clin Exp Allergy* 1999, **29**, 347-356.

20. Fornaciari M, Orlandi F, Romano B: *A National Project to forecast regional olive production by pollen monitoring. Abstracts of the Second European Symposium on Aerobiology, September 2000*, Vienna, Austria.

21. Fornaciari M, Pieroni L, Ciuchi P, Romano B: A statistical model for correlating airborne pollen grains (*Olea europaea* L.) with some meteorological parameters. *Agr Med* 1997. **127**, 134-137.

22. Galán C, Fuillerat MJ, Comtois P, Domínguez E: A predictive study of Cupressaceae pollen season onset: severity, maximum value and maximum value date. *Aerobiologia* 1998, **14**, 145-199.

23. Galán C, Cariñanos P, García-Mozo H, Alcázar P, Domínguez E: Model for forecasting *Olea europaea* L. airborne pollen in South-West Andalusia, Spain. *Int J Biometeorol* 2001, **45(2)**, 59-63.

24. Galán C, García-Mozo H, Vázquez L, Ruiz L, Díaz de la Guardia C, Trigo MM: Heat requirement for the onset of the *Olea europaea* L. pollen season in western Andalusia and the effect of the expected future climate change. *Int J Biometeorol* 2005, **49(3)**, 184-188.

25. García-Mozo H, Galán C, Cariñanos P, Alcazar P, Méndez J, Vendrell M, Alba F, Sáenz C, Fernández D, Cahezudo B. Domínguez-Vilches E: Variations in the *Quercus* sp pollen season at selected sites in Spain. *Polen* 1999, **10**, 59-69.

26. García-Mozo H, Galán C, Gómez-Casero MT, Domínguez E. A comparative study of different temperature accumulation methods for predicting the *Quercus* pollen season start in Córdoba (Southwest Spain). *Grana* 2000, **39**, 194-199.

27. García-Mozo H, Galán C, Aira MJ, Belmonte J, Díaz de La Guardia C, Fernández D, Gutiérrez AM, Rodríguez FJ, Trigo MM, Domínguez-Vilches E: Modelling start of oak pollen season in different climatic zones in Spain. *Agric Forest Meteorol* 2002, **110**, 247-257.

28. Giannini R, Magnani F: Impact of global change on pollination processes and on the genetic diversity of forest tree populations. *Forest Genet* 1994, **1(2)**, 97-104.

29. Gómez-Casero MT, Hidalgo P, García-Mozo H, Domínguez E, Galán C: Pollen biology in four Mediterranean *Quercus* species. *Grana* 2004, **43**, 1-9.

30. Gómez-Casero MT, Vázquez L, Galán C, Domínguez E: *Comportamiento fenológico del género Quercus en la Sierra de Córdoba. Relación con su contenido polínico en la atmosfera. XIV Symposium of the Spanish Association of Palinology*. September 2002, Salamanca, Spain.

31. Hennessy KJ, Gregory JM, Mitchell JFB: Changes in daily precipitation under enhanced greenhouse conditions. *Clim Dynamics* 1997, **13**, 667-680.

32. Hidalgo P, Mangin A, Galán C, Hembise O, Vázquez L, Sánchez O: An automated system for surveying and forecasting *Olea* pollen dispersion. *Aerobiologia* 2002, **18**, 23-31.

33. Jäeger S: *Long term trends of pollen seasons in Europe: Changes in start, duration and intensity. Abstracts of the 7th International Congress on Aerobiology.* August 2002, Montebello, Canada.

34. Jato V, Aira MJ, Iglesia MI, Alcázar P, Cervigón P, Fernández D, Recio M, Ruiz L, Sba L: Aeropalynology of Birch (*Betula* sp.) in Spain. *Polen* 1999, **10**, 39-58.

35. Jato V, Rodríguez FJ, Méndez J, Aira MJ: Phenological behaviour of *Quercus* in Ourense (NW Spain) and its relationship with the atmospheric pollen season. *Int J Biometeorol* 2002, **46**, 176-184.

36. Jones PD. New M, Parker DE, Martin S, Rigor IG: Surface air temperature and its changes over the past 150 years. *Rev Geophysics* 1999, **37**, 173-199.

37. Leventin T: A long term study of winter and early spring tree pollen in the Tulsa, Oklahoma atmosphere. *Aerobiologia* 1998, 14, 21-28.

38. Luseri ME, Li Bianchi E, Fanti A, Scamatti C, Cecconi ME, Marinelli MA: Tree pollen allergy in Roma. *Allergy* 1996, **51(Suppl)**, 389.

39. Martínez Cocera C: Socio-economical impact of allergy diseases. *Allergol Immunol Clin* 2002, **17(2)**, 1-29.

40. Matthiesen F, Ipsen H, Lowenstein H: Pollen allergens: **In:** D'Amato G (Ed.): *Allergenic pollen and pollinosis in Europe*, 36-44. Blackwell Scientific Publications, Oxford 1991.

41. Menzel A, Fabian P: Growing season extended in Europe. *Nature* 1999, **397**, 501-504.

42. Moreno JM: *Evaluación de los Impactos del Cambio Climático en España. ECCE.* Ministerio de Medio Ambiente, Madrid 2005

43. Moseholm L. Weeke ER, Petersen BN: Forecast of pollen concentrations of Poaceae (Grasses) in the air by time series analysis. *Poll Spores* 1987, **29**, 305-322.

44. Mothes N. Valenta R: Biology of Tree Pollen Allergens. *Curr Allergy Asthma Rep* 2004, **4**, 384-390.

45. Nakicenovic N, Alcamo J, Davis G et al. (Eds): *IPCC Special Report on Emission Scenarios*, 99-181. Cambridge University Press 2001.

46. Negrini AC, Arobba D: *An Illustrated Guide to Pollen Analysis.* Hodder and Stoughton eds, London 1992.

47. Osborne CP. Chuine I, Viner D, Woodward FI: Olive phenology as a sensitive indicator of future climate warming in the Mediterranean. *Plant Cell Environ* 2000, **23**, 701-710.

48. Met Office: *PRECIS Providing Regional Climates for Impact Studies. The Hadley Centre regional climate modelling system.* Met Office: Bracknell, Berkshire 2001.

49. Prentice IC, Farquar GD, Fasham MJR *et al*.: The carbon cycle and atmospheric carbon dioxide. **In:** Houghton JT, Ding Y, Griggs DJ, Noguer M. Van der Linden PJ, Dai X, Maskell K, Johnson CA (Eds) *Climate Change 2001: The Scientific Basis, Contribution of Working Group of the IPCC*, 183-237. Cambridge University Press, Cambridge 2001.

50. Recio M. Trigo MM, Toro J, Cabezudo B: Airborne pollen of *Quercus* in Malaga (S. Spain) and its relationship with meteorological parameters. *Acta Botanica Malacitana* 1999, **24**, 77-88.

51. Río S: *The climatic change and its influence on the vegetation of Castilla-Leon*. Doctoral Thesis. University of Leon, Leon 2003.

52. Ross AM, Corden JM, Fleming DM: The role of oak pollen in hay fever consultances in general practice and the factors influencing patients' decisions to consult. *Br J Gen Pract* 1996, **46**, 451-455

53. Schwartz MD: Advancing to full bloom: planning phenological research for the 21st century. *Int J Biometeorol* 1999, **42**, 113-118.

54. Schwartz MD: Green-wave phenology. *Nature* 1998, **394**, 839-840.

55. Spieksma FTh, Emberlin J, Hjelmroos M, Jäger S, Leuschner RM: Atmospheric birch (*Betula*) pollen in Europe: trends and fluctuations in annual quantities and the starting dates of the seasons. *Grana* 1995, **34**, 51-57

56. Subiza E, Subiza FJ, Jerez M: Palinologia: **In:** SEAEIC (Ed): *Tratado Alergologia e Inmunologia Clínica. Tomo IV*, 211-255. Madrid 1987.

57. Subiza J, Jerez M, Jimenez JA, Narganes MJ, Cabrera M, Varela S, Subiza E: Allergenic pollen pollinosts in Madrid. *J Allergy Clin Immunol* 1995, **96(1)**, 15-23.

58. Tormo R, Muñoz A, Silva I, Gallardo F: Pollen production in anemophilous trees. *Grana* 1996, **35**, 38-44.